Investment perspectives on costs for air pollution control affect the optimal use of emission control measures

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ORIGINAL PAPER

Investment perspectives on costs for air pollution control affect the optimal use of emission control measures

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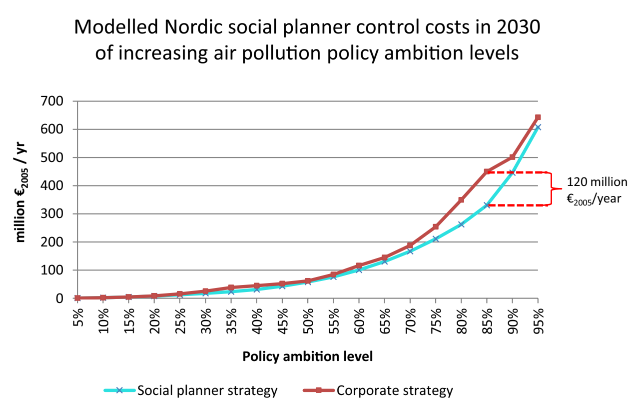
Abstract

Cost-effective air pollution emission control has been in focus for decades in international air pollution regulations. Despite large observed emission reductions for many air pollutants, environmental and human health problems persist and more efforts are needed. However, some stakeholders are concerned that the costs for remaining emission control measures are prohibitively high. There are several reasons for concern, and one can be the difference in investment perspectives—i.e. costs of borrowing and time constraints—held by stakeholders. By using the integrated assessment model GAINS, we study whether differences in investment perspectives of Nordic stakeholders influence measures selected for cost-effective emission control and can motivate concerns for high costs of emission control. We distinguish the control cost calculations between a social planner perspective and a corporate perspective and apply these to the GAINS model database on emission control measures. A cost-minimized selection of measures in 2030 is then calculated for increasing environmental and health ambitions for both perspectives. The results show an irregular pattern, but for a range of ambition levels the corporate perspective affects the selection of measures and implies surplus costs for the Nordic social planner of up to 120 million € per year. This is 36% more expensive than the costs of the social planners' selection. Conversely, from a corporate perspective the social planners' selection can imply cost increases of up to 180 million €. We therefore suggest that control of investment perspective effects should be standard in analysis of cost-effective air pollution measures.

Graphical abstract



Keywords Cost-effective emission control · Cost-effective policy · Investment perspectives · Time perspective · Air pollution policy

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Extended author information available on the last page of the article

Introduction

Cost-effectiveness of pollution control is an important criteria when setting policy ambition levels in the Gothenburg Protocol of the Air Convention (United Nations 2013) and the EU National Emission Ceilings (NEC) Directive (Official Journal of the European Union 2016), both controlling European emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), fine particular matter ($PM_{2.5}$), and non-methane volatile organic compounds (NMVOCs). Given the site-specific nature of air pollution dispersion, damages, and emission control, the international policy and research community use integrated assessment models (IAMs) such as the Greenhouse Gas—Air Pollution Interactions and Synergies (GAINS) model (Amann et al. 2011) to analyse cost-effectiveness of different policy options. Since cost-effectiveness has been a guiding principle of both the Air Convention and EU air pollution policies for decades, the conventional (end-of-pipe) measures that are considered still available for implementation are in general more expensive than already implemented measures. If costs are perceived as too high, this can lower the ambition level reached in future international agreements, and one of the reasons to why costs can be perceived as too high is that stakeholders and decision-makers have different perspectives on emission control costs.

Two common perspectives used when calculating and comparing emission control costs are the social planner perspective and the corporate (private sector) perspective. Although likely based on the similar cost calculation principles (Graham and Harvey 2001), the two perspectives differ with respect to risk and time constraints, as well as costs of acquiring financial resources for investments (Grout 2003). In integrated assessment modelling, these differences mainly imply that different interest rates and time constraints are used in calculations. Although no strict definition of the social planner seems to exist, in our paper the social planner tries to achieve the largest benefit for society by reducing emissions where the largest impact on the environment and human health can be achieved at the lowest costs, with cheap access to capital (low interest rates) and long-term time constraints.

The social planner perspective on investments is common in analysis of emission control costs. This custom enables an analysis to: allow for equal comparison of costs between countries and sectors; consider the fact that governments with cheap access to financial resources have control over policy instruments; and avoid financial transactions to be included as costs in calculations of emission control costs. In contrast, actual decisions on which measures to invest in are to an increasing extent made by corporations operating under profit-maximizing conditions (with high interest rates) and with short-term time constraints, which implies a different perspective on investments.

Correspondingly, the emission control costs of a control measure as perceived from the corporate perspective might differ substantially from the costs perceived from the social planner perspective. Conceptually, the corporate perspective implies that from a set of measures, those characterized by low investment costs and high costs for operation and maintenance are preferred over measures characterized by high investment costs and low costs for operation and maintenance. This is due to the high interest rate and desired short payback time on investments. For the social planner perspective, the opposite is true. Corporations might therefore perceive the social planners' cost-effective selection of measures as expensive, only because of the different perspectives. It is, however, not evident that this conceptual difference will materialize in an environmental policy context.

The environmental and social impact of the differences between investment perspectives of a social planner and other decision-makers is sparsely studied, while some (if not many) impact analyses are using only one perspective without presenting any sensitivity analysis: McCollum et al. (2013), van Vuuren et al. (2007), West et al. (2013) and Zhang et al. (2018) are examples of this. Goeschl and Swanson (2002) found that private firms will underestimate the social value of biodiversity available for research and development due to differences in perspectives on investments. Similar but more generic results were also found in Delbono and Denicolo (1991). Results from the few studies analysing how interest rates might affect investment choices and policy recommendations are mixed. van Harmelen et al. (2002) controlled for the impacts of interest rates and found that '*The choice of the interest rate of 4% has only a minor influence on the technology mix*', and Markandya et al. (2018) noticed that a discount rate variation of 0–6% had little impact on results. Stocks (1984), however, showed how the cost-optimal choice of energy technologies in an Australian energy system would differ substantially depending on the discount rate used in the cost calculations, with similar results shown for British utilities in Dimson (1989). Further, de Vries et al. (2007) showed how global future estimated potential of wind power and solar photo voltaic is affected by interest rates. Höglund-Isaksson (2012) presented global control cost curves for control of methane (CH_4) and explicitly separated the social planner investment perspective from the private sector perspective. As expected, Höglund-Isaksson (2012) showed (inter alia) that social planner costs are lower than private sector costs. More interesting though, when reviewing the results from Höglund-Isaksson (2012) it is also clear that the control measures considered cost-effective differ between perspectives. Seventeen out of 30 measures change their cost-effectiveness ranking depending on investment perspective. This could imply that for any given CH_4 target, the measures advocated as suitable for cost-effective policy would differ. It also implies that society might end up paying more than necessary for emission reductions (i.e. facing surplus costs for emission control). These implications are also imaginable for multi-pollution policies such as air pollution policy. And it is, for the air pollutants discussed in this paper, possible that investment perspectives might affect both where cost-effective emission reductions take place and which pollutants that are reduced.

Therefore, in this paper, we study with the GAINS model to what extent differences between social planner and corporate investment perspectives affect the modelled total costs for society of reducing emissions. We also study potential impacts of perspectives on control costs per country and sector, the cost-optimal combination of measures, as well as pollutants controlled.

Which numerical value of the interest rate that represents the respective perspectives is subject to a long academic debate (Baumol 1968; Grout 2003; Jensen and Bailey 1972; Moore et al. 2013; Moore et al. 2004; Spackman 2004). Formally in the analysis presented in this paper, the social planner perspective implies a 4% interest rate on investment (Godard 2009), which is close to other common literature values of 3.5% (Moore et al. 2004) and corresponds to the value chosen in contemporary air pollution policy analysis (Amann 2015). The time constraints of the social planner imply that the entire technical lifetime of control measures is considered. The corporate perspective implies a 10% interest rate (Boardman et al. 2001) and an economic lifetime of control measures of up to 10 years (Höglund-Isaksson 2012), reflecting higher costs for capital and lower ability to accommodate risks.

We choose to delimit our study to the NEC Directives' policy target year 2030 and the countries Denmark, Finland, Norway, and Sweden (together called Nordic in this paper), most of which are still in 2030 projected to have problems with acidification in addition to problems with human health due to air pollution (Fölster et al. 2014; Norwegian Environment Agency 2018; Swedish Environmental Protection Agency 2015). We also limit the analysis by including only conventional and well-defined (mainly end-of-pipe) measures for air pollution control. These types of measures are important in the air quality policy agenda, and the knowledge about them is sufficient for IAM of cost-effective air pollution control. Other types of measures such as structural and behavioural measures are, although important for future air quality, not included in this analysis due to lack of systematic Nordic-wide knowledge of their costs, effects, future potential, and applicability. Furthermore, the Nordic countries have since many years invested in emission control, and the remaining end-of-pipe control measures are therefore relatively few. Consequently, there is less potential impact of investment perspectives on cost-optimal measures and surplus costs than if emissions would have been uncontrolled and all measures would be available for implementation.

Method and data

With the GAINS model, we calculate scenarios of cost-effective use of emission control measures for different policy ambition levels in 2030, ranging between a Current Policy ambition level and 100% policy ambition level. The calculations are done either with the investment perspective of a social planner (4% interest rate and technical lifetime of investment) or corporations (10% interest rate and 10-year lifetime). For each ambition level, we compare the perspectives mainly with respect to control costs. The comparison identifies potential social planner surplus costs of the corporate perspective and corporate cost increase in the social planner perspective. We also compare the cost-optimal combination of measures (strategies) and emission levels.

Scenario description

As a basis for all scenarios in this paper, we use an exogenous scenario on emission-driving activities (such as fuel use, transportation, and industrial and agricultural production) with input from Amann (2015) for Denmark, Finland, and Sweden, and from Amann et al. (2013) for Norway. Most noticeable in this exogenous scenario is that nuclear power is increasing, fuel use for light duty road transport is decreasing, production in oil refineries is decreasing, and livestock is increasing (Fig. 1).

For the scenarios in this paper, we use the GAINS model database information to calculate air pollution emissions and control costs, specific for each policy ambition level and investment perspective. For the Current Policy ambition level, the use of emission control measures and the emissions of air pollutants in the Nordic countries are preset and identical in the social planner and corporate perspectives. The Current Policy ambition level is constructed based on current understanding on 2030 impacts from existing policies to control acidification, eutrophication, and air pollution-related human health (Amann 2015; Amann et al. 2013; Kiesewetter et al. 2015). For the 100% ambition level, all technically available control measures would be used in 2030, implying that the social planner and corporate perspectives again lead to identical selection of measures. Correspondingly, the 100% ambition level results in the lowest technically achievable human health and environmental impact due to air pollution out of all ambition levels, given the model used.

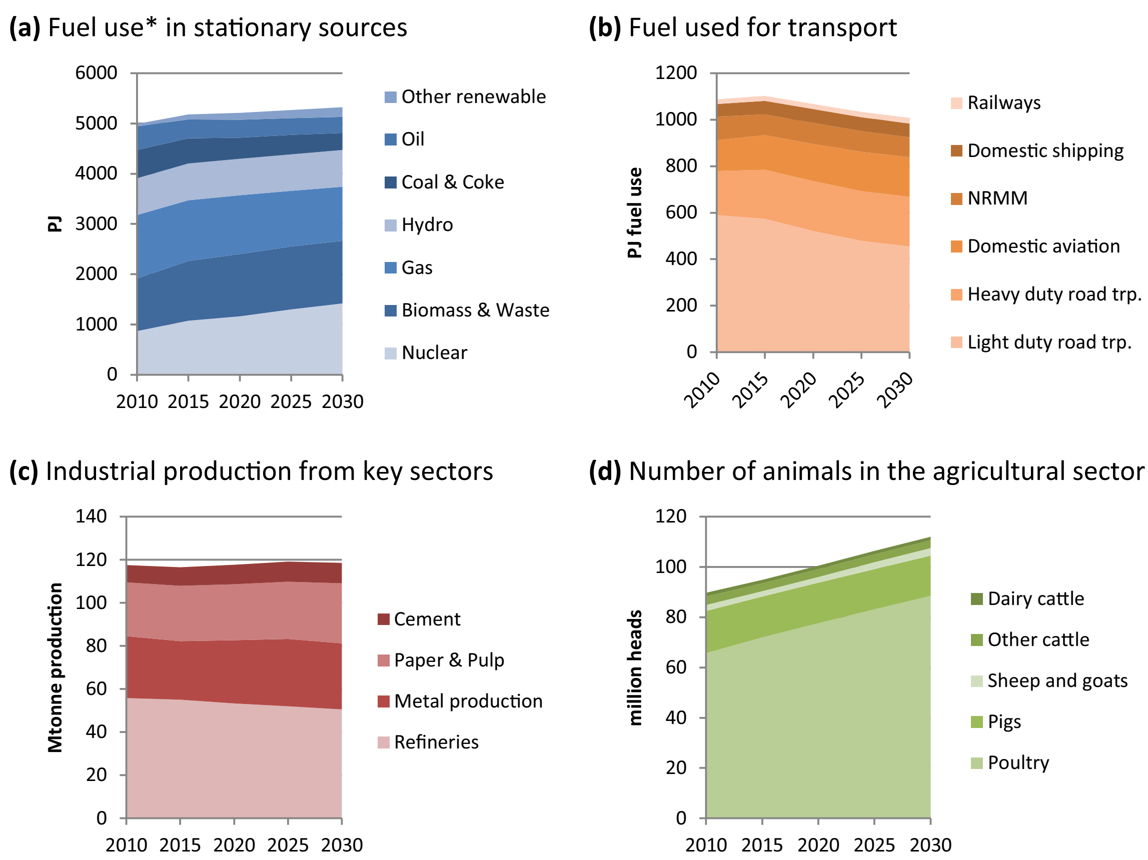

Fig. 1 Aggregated extract of the most pertinent exogenous scenario data for the four Nordic countries for the years 2010–2030. **a** Electricity and heat generation: primary fuel use in combustion and nuclear power, and (*) electricity generation from hydro; **b** primary fuel used in transport (*NRMM* non-road mobile machinery; **c** industrial production of cement, paper and pulp, metals, and refined oil products (other production excluded from the graph in the interest of brevity); **d** number of animals held for meat and milk production

We then analyse cost-effective control costs for the ambition levels in between the Current Policy and the 100% ambition levels in 5% increments. The percentage value refers to the improvement of human health and environmental integrity achieved by the ambition level relative to the improvement reached in the 100% ambition level. These calculations are done separately for the social planner and corporate perspectives. For each analysed ambition level, the cost-effective use of available control measures is thereby differentiated between a social planner strategy and a corporate strategy.

Calculation of emissions, ambient concentrations, and control costs

The GAINS model databases contain information on emission factors, emission control measures and their costs, geographical emission dispersion patterns, as well as on human health and environmental sensitivity to air pollution. The calculation of emissions is done with the following equation:

$$E_i = \sum_{j,k,m} E_{i,j,k,m} = \sum_{j,k,m} A_{i,j,k} \cdot \mathrm{ef}_{i,j,k} \cdot \left(1 - \mathrm{eff}_m\right) \cdot x_{i,j,k,m} \tag{1}$$

where i, j, k, m = country or sea region, sector, activity type, control measure; E_i = emissions in country i [ktonne]; A = activity in a given sector [PJ fuel or other units corresponding to the activity driving emissions]; ef = emission factor when not using any control measure [ktonne/unit of emission-driving activity]; eff = emission reduction efficiency of measure m [%]; x = implementation rate of the considered control measure m, and of the residual no-control option [%].

After having calculated emissions from a country, concentration and deposition of pollutants in receptor regions are calculated in the optimization by linear form emission dispersion patterns between countries (Eq. 2 shows an example for calculation of $PM_{2.5}$ concentration):

$$\mathrm{PM_r} = \sum_i \mathrm{pm}_i \cdot P_{i,\mathrm{r}} + \sum_i s_i \cdot S_{i,\mathrm{r}} + \sum_i a_i \cdot A_{i,\mathrm{r}} + \sum_i n_i \cdot N_{i,\mathrm{r}} + \sum_i v_i \cdot V_{i,\mathrm{r}} + k_{0,\mathrm{r}} \tag{2}$$

where r = receptor region; $\mathrm{PM_r}$ = concentration of $PM_{2.5}$ in receptor region r [μg/m^3]; pm_i = emissions of primary $PM_{2.5}$ in country i [ktonne]; s_i = emissions of SO_2 in country i

[ktonne]; a_i = emissions of NH_3 in country i [ktonne]; n_i = emissions of NO_x in country i [ktonne]; v_i = emissions of NMVOC in country i [ktonne]; $k_{0,r}$ = background concentration constant in region r [μg/m^3]; P, S, A, N, V = transfer coefficients between source region i and receptor region r [μg/m^3/ktonne], for the different pollutants PM, SO_2, NH_3, NO_x, NMVOC.

Impacts on human health, acidification, and eutrophication (of which improvements are the objective of the policy ambition) are then calculated by comparing the calculated concentration and deposition of air pollutants in the receptor regions with database information on ecosystem sensitivities and population densities. For a detailed description of the impact calculations, see Kiesewetter et al. (2015). For the purpose of the control cost optimization, region-to-grid coefficients including a downscaling of contributions from low-level primary $PM_{2.5}$ emissions as described by Kiesewetter et al. (2015) are aggregated to region-to-region coefficients.

For each of the 5–95% ambition levels, we calculate cost-effective emission control strategies through linear cost minimization. The optimization takes into account (inter alia): the measures already used in the Current Policy ambition level; that some measures affect emissions of several pollutants; atmospheric interactions of air pollutants; as well as differences in environmental sensitivity and population sizes between receptor regions (Wagner et al. 2013).

Of specific relevance for this paper is how emission control costs are calculated. For each measure (m) available to reduce emissions from one unit of emission-causing activity type (k), annual unit control costs are calculated as:

$$\mathrm{UC}^{\mathrm{an}} = \mathrm{UC}^{\mathrm{O\&M}} + I \cdot \frac{(1+q)^{\mathrm{lt}} \cdot q}{(1+q)^{\mathrm{lt}} - 1} \tag{3}$$

where $\mathrm{UC}^{\mathrm{an}}$ = annual unit control cost [Million €$_{2005}$/year]; $\mathrm{UC}^{\mathrm{O\&M}}$ = annual unit costs for operation and maintenance of the measure [Million €$_{2005}$/year]; I = investment expenditure on the measure [Million €$_{2005}$]; q = interest rate on investment [%] (social planner $q = 4\%$; corporate $q = 10\%$); lt = economic lifetime of measure [years] (social planner lt = technical; Corp lt = <10 years),

The second term in Eq. 3 corresponds to annualized investments.

The total annual cost (C) for each measure is then given for each country (i) by multiplying the activity level of the relevant polluting activity with $\mathrm{UC}^{\mathrm{an}}$ and the implementation rate x in Eq. 1 of the measure. The principle of the optimization is then to minimize total annual cost for air pollution control by varying x. The most important constraints to the optimization are technical feasibility as given by the 100% policy ambition scenario, as well as impacts on human health, acidification and eutrophication as derived from the percentage specification of each policy ambition (Eq. 4, Amann et al. (2011)):

$$\sum_i \sum_k \sum_o C_{i,k,o} \rightarrow \min \tag{4}$$

Analysis of potential surplus costs and cost increases

To analyse whether investment perspectives affect the cost-optimal combination of measures and thereby control costs, we re-use the cost-optimal control solutions from the corporate strategy but apply the cost setting of the social planner perspective to calculate social planner costs of the corporate strategy. We use the term 'surplus costs' to indicate the difference between the social planner costs of a corporate strategy and the social planner costs of a social planner strategy. For comparison, we also reverse the procedure to find the corporate costs from implementing the social planner strategy, with the difference between strategies denominated as 'cost increases'.

Sensitivity analysis of control costs

In the sensitivity analysis, we vary operation and maintenance costs as well as annualized investment with ± 10% independently. The variation of the annualized investment with ± 10% corresponds to q having the value 3% or 5% in the social planner perspective and 8% or 12% in the corporate perspective. This sensitivity analysis thereby checks for robustness of modelled selection of control measures with respect to cost uncertainties.

Data on measure-specific emission control costs

The cost calculations are based on data from Amann (2015). All the input data used to calculate emissions and emission control costs, as well as maximum use of control measures, are publicly available online at GAINS Europe[1] in the scenario group TSAP_Nat_Consultation_2014. Specific information on control measures, costs, and effect on emissions are for NO_x taken from Cofala and Syri (1998a), for SO_2 Cofala and Syri (1998b), for $PM_{2.5}$ Klimont et al. (2002) and Cofala et al. (2006), and for NH_3 Klimont and Winiwarter (2011). Aggregated results on emissions and control costs as presented in the source literature are shown in Table 1.

[1] Online access to GAINS Europe: http://gains.iiasa.ac.at/gains/EUN/index.login?logout=1&switch_version=v0 . GAINS is openly accessible (registration required).

Table 1 Nordic emission trend 2010–2030 and emission control costs according to current legislation and alternative 2030 emissions and control costs in a Maximum Technical Feasible Reduction (MTFR) scenario (Amann 2015; Amann et al. 2013). Current legislation corresponds to Current Policy ambition in this paper, and MTFR corresponds to 100% policy ambition. The costs are calculated with a social planner perspective

	Year						Unit
			Current legislation			MTFR	
	2010	2015	2020	2025	2030	2030	
Emissions							
NO_x	627	534	431	367	334	271	ktonne
SO_2	137	117	109	107	105	94	ktonne
NH_3	177	169	164	167	167	123	ktonne
NMVOC	505	436	374	358	337	293	ktonne
$PM_{2.5}$	138	126	114	112	107	80	ktonne
Costs	3932	4597	5089	5411	5581	6897	million €$_{2005}$/yr

Results

Our model calculations show that the investment perspective has an impact on emission control costs for some, but not all, policy ambition levels, as is shown in Fig. 2. There are two major deviations from the costs of the social planner strategy if Nordic emission reductions are achieved with the corporate strategy. At 35% ambition level, surplus costs for society of the social planner strategy are 24 million €$_{2005}$ per year and the corporate strategy is 62% more expensive. At 85% ambition level, a social planner strategy costs 331 million €$_{2005}$ per year and the corporate strategy is 36% more expensive. In between these two deviations, the costs are fairly similar, so some modelled policy ambition levels appear relatively robust with respect to investment strategies for the social planner.

Conversely, the social planner strategy would lead to corporate cost increases when costs are recalculated using the corporate perspective. But as Fig. 3 shows, the cost increases from the optimal corporate strategy of a social planner strategy would be relatively evenly distributed for all of the more ambitious policy ambition levels. Meaning most of the modelled ambitious social planner strategies appears to be unnecessarily expensive from a corporate perspective.

The differences in control costs are caused by different cost-effective combinations of measures in the respective strategies. Here, we present these differences for the strategies used to reach an 85% policy ambition level. The result from the sensitivity analysis on cost-optimal control measures is presented within brackets in the text and tables and as error bars in Fig. 4.

For the 85% ambition, the surplus costs from using a corporate strategy are unevenly distributed over the countries. At this ambition level, the social planner surplus costs would be 105 (99–105), 13 (6–16), and 17 (16–28) million €$_{2005}$ in Denmark, Norway, and Sweden, respectively, if a corporate strategy would be used, but decrease by − 16 (− 15 to − 24)

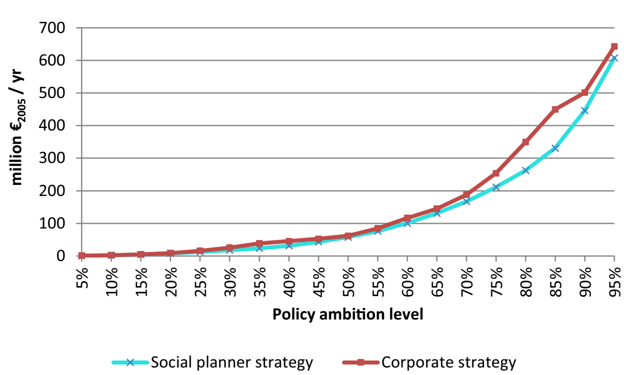

Fig. 2 Social planner control costs in 2030 of increasing air pollution policy ambition levels (increasing from 5 to 95%) if using a social planner strategy or a corporate strategy. In the figure, it can be seen that the social planner surplus costs of the corporate strategy are irregular and highest at the 85% policy ambition level

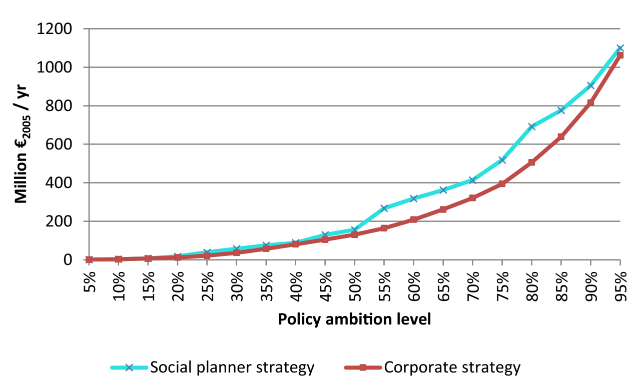

Fig. 3 Corporate perspective control costs in 2030 of increasing air pollution policy ambition levels (increasing from 5 to 95%) if using a social planner strategy or a corporate strategy. The corporate cost increase in the social planner strategy is irregular over ambition levels but more evenly spread out than in Fig. 2

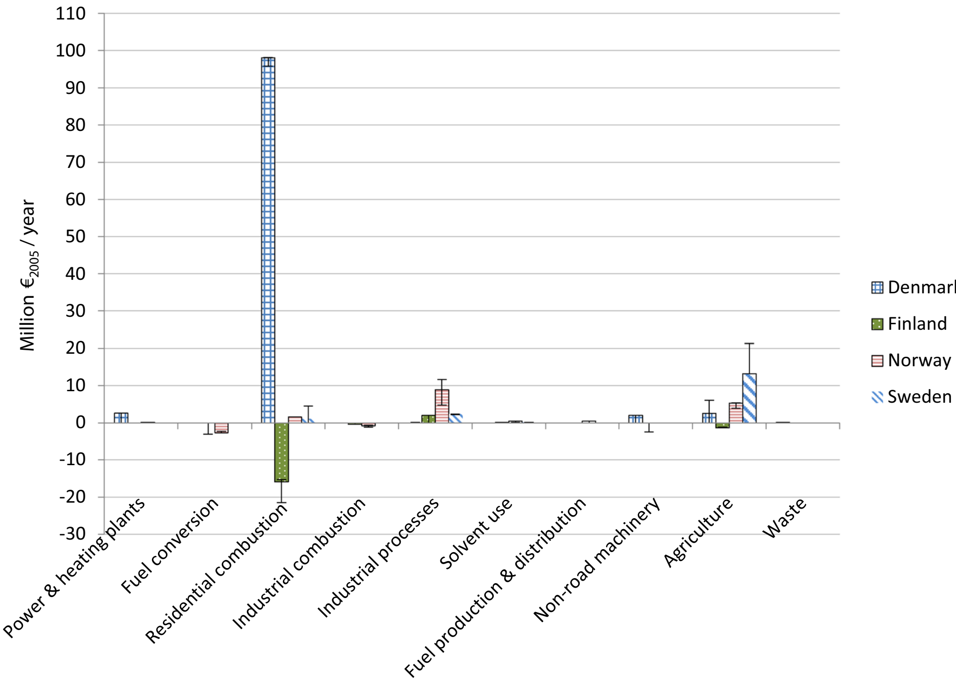

Fig. 4 Social planner control cost changes at an 85% policy ambition level if using the corporate strategy instead of the social planner strategy. Costs are presented per country and sector. The whiskers present the variation as given by the technology selections in the sensitivity analysis. Most importantly, the corporate strategy implies higher efforts to control emissions from Danish residential combustion, Norwegian industrial processes, and Swedish agricultural activities than the social planner strategy but less efforts for Finnish residential combustion. Also interesting is that for the 85% ambition level, no real differences between strategies are found for the emitting sectors: solvent use; fuel production; and waste

million €$_{2005}$ in Finland. For the entire region, social planner surplus costs would be 119 (98–134) million €$_{2005}$. There are also differences in which sector the cost differences occur (Fig. 4).

When comparing cost-effective measures, it can be seen that in the model calculations of the 85% ambition level the most significant impact of investment perspectives is found with the corporate strategy's increased use of cleaner stoves and fireplaces in the Danish residential sector, which reduce emissions of $PM_{2.5}$ and NMVOC.

But there are also a number of other but smaller differences between the two strategies. For Finland, the corporate strategy mainly implies lower use of the same measures in residential combustion, which is also the case for Norway, with corresponding increase in $PM_{2.5}$ and NMVOC emissions. For Norway, also NO_x emissions from industry increase, but through reduced focus on combustion modification in boilers and other industrial combustion compared to the social planner. However, through increased use of low sulphur fuels, covering of manure storage as well as biofiltration, the corporate strategy leads to lower Norwegian emissions of SO_2 and NH_3, respectively. For Sweden, the most significant change with the corporate strategy is a reduction of NO_x emissions from cement production, but also NH_3 emissions go down slightly through improved and combined agricultural practices.

Consequently, the investment perspective has an impact on modelled national total levels of emissions at the 85% ambition level (Table 2) as well as for several other ambition levels (supplementary material). For Denmark and the 85% ambition level, the corporate strategy implies larger focus on reduction of NH_3, $PM_{2.5}$, and NMVOC, while for Finland the situation is reversed. Finland is also reducing less NO_x emissions with the corporate strategy than with the social planner strategy. The corporate strategy also implies that Norway reduces more emissions of SO_2 and NH_3 than with the social planner strategy, while Sweden reduces more emissions of NO_x and NH_3. For the entire region, the social planner strategy implies focus on control of NO_x, $PM_{2.5}$, and NMVOC, whereas the corporate strategy puts more focus on SO_2 and NH_3.

Discussion

Our results show that the investment perspective chosen for control cost calculation with the GAINS model has an impact—although irregular—on total control costs, the combination of measures considered cost-effective, in which country and sector emission reductions take place, and which pollutants are reduced. More specifically, if considering surplus costs of at least 20% as a lower boundary for significant differences between strategies, there are 9 out of 19 analysed policy ambition levels where investment perspectives have an impact on costs and control measures. The lowest modelled ambition level with significant surplus costs is 25% and the highest 85%, with non-significant differences in the 50–70% range. For the entire Nordic region, the corporate strategy to reach 85% ambition level implies larger efforts to control NO_x, $PM_{2.5}$, and NMVOC emissions, but there are variations between countries. At 85% ambition level, the main impact of the

Table 2 National total 2030 emissions per country and per investment strategy for the 85% ambition level (ktonne). The strategy leading to the largest emission reductions marked with bold for each pollutant and country. Results from the sensitivity analysis within brackets

	Denmark	Finland	Norway	Sweden	Nordic total
SO_2					
Soc.	7.9 (7.9–7.9)	41.0 (41.0–41.0)	18.0 (18.0–18.0)	30.0 (29.9–30.3)	96.9 (96.8–97.2)
Corp.	7.9 (7.9–7.9)	40.1 (40.1–41.0)	**17.0** **(16.9–17.2)**	29.9 (29.9–29.9)	**94.9** **(94.8–96.0)**
NO_x					
Soc.	56.0 (55.9–56.0)	**92.6** **(91.8–92.6)**	**113.2** **(113.2–113.8)**	66.4 (66.4–66.4)	**328.2** **(327.3–328.8)**
Corp.	55.9 (55.9–55.9)	93.6 (92.9–93.6)	118.6 (118.6–118.7)	**65.2** **(65.2–65.2)**	333.3 (332.6–333.4)
NH_3					
Soc.	42.8 (42.8–43.1)	**28.3** **(28.3–28.3)**	18.2 (18.2–18.2)	37.3 (37.3–37.3)	126.6 (126.6–126.9)
Corp.	**42.6** **(42.6–42.7)**	28.4 (28.4–28.4)	**17.9** **(17.9–17.9)**	**36.4** **(36.1–36.4)**	**125.3** **(125.0–125.4)**
$PM_{2.5}$					
Soc.	9.7 (9.6–9.7)	**19.1** **(19.1–19.1)**	**36.0** **(36.0–36.0)**	17.3 (17.3–17.3)	**82.1** **(82.0–82.1)**
Corp.	**8.9** **(8.9–8.9)**	20.4 (20.3–20.5)	36.8 (36.8–36.8)	17.3 (17.3–17.3)	83.4 (83.3–83.5)
NMVOC					
Soc.	51.4 (51.4–51.4)	**52.6** **(52.6–52.6)**	93.6 (93.6–93.6)	118.3 (118.3–118.3)	**315.9** **(315.9–315.9)**
Corp.	**50.5** **(50.3–50.5)**	59.4 (59.4–59.6)	90.3 (90.3–94.3)	118.3 (118.3–118.3)	318.5 (318.3–322.7)

corporate strategy is that it implies larger focus on controlling $PM_{2.5}$ emissions from Danish residential combustion and Swedish NH_3 emissions from agriculture, and smaller focus on reducing $PM_{2.5}$ emissions from residential combustion in Finland.

The irregularity of surplus costs over ambition levels is not surprising given the expected limitation in available measures in the Nordic countries by 2030. In the Current Policy ambition level—which is the starting point of our analysis—only an average of ~30% of all measures in the model database is available as a response to increased policy ambition. If the number of available measures had been larger, i.e. with a less ambitious Current Policy situation, it is likely that the impact of investment perspectives would be larger and also more regular. Our results match well with the findings of Höglund-Isaksson (2012), and they also give a potential explanation for why other studies have shown contradicting results. Bearing in mind the irregularity of our results over ambition levels, it is perfectly possible that the non-impact of changing interest rates in van Harmelen et al. (2002) and Markandya et al. (2018) is consistent with the large impact of varying discount rates presented in Stocks (1984), Dimson (1989), and de Vries et al. (2007).

One limitation of the analytical approach in this paper is that mainly end-of-pipe emission control measures are included in the analysis. However, to focus on this type of measures is consistent with the current focus on best available emission control technologies in existing European air pollution policies (EC JRC 2016; UNECE 2015, 2016), and the existing European policy distinction between climate and air pollution challenges. This distinction is, however, known to reduce cost-effectiveness of policies (Zusman et al. 2013) and also limits the policy push for using climate measures to help reach air pollution objectives and vice versa. The focus on end-of-pipe also ensures the estimate of surplus costs to be on the cautious side. As is discussed above, more available measures will decrease the irregularity and likely increase relative surplus costs of corporate strategies. Furthermore, we only compare two investment perspectives which are separated only through two parameters (interest rate and time constraints). If we included the investment perspective of individuals/households (typically facing even higher interest rates and more short-sighted), the impact should be larger. The impact of our two-parameter description of perspectives is unclear, but given that the GAINS model method for calculating costs appears to be similar to the methods used by corporations (Graham and Harvey 2001), we think that a more complex description should give similar results. Finally, the presented numerical impact on costs, measures, and emissions is specific to the expected situation in the Nordic countries 2030; therefore, the possibility of a quantitative generalization is limited.

There are several implications of our results. First of all, the fact that investment perspectives can affect modelled efforts per country and pollutants prioritized is important for international air pollution policy since current policies, such as the NEC directive, specify efforts per country and pollutant. Second, the results support the suspicion that investment perspectives might affect the total costs for society of reducing emissions. For several modelled ambition levels, the measures considered cost-effective by the social planner are different from the measures considered cost-effective by corporations, despite the large number of measures already implemented in the Current Policy ambition level. Third, there are modelled ambition levels with little impact of investment perspectives. These ambition levels should have higher chances of emissions being controlled with the measures prescribed by the social planner than other ambition levels, regardless of investment perspective (within reasonable limits). This in turn should increase robustness and acceptance by stakeholders of these ambition levels. Finally, the results point to the importance of clearly expressing which investment perspective (interest rates and economical life times) that is used when calculating cost-effective emission control, and to the importance of making sensitivity analysis over these economic parameters prior to drawing policy recommendations from cost-effectiveness analysis. Since it is more and more common that corporations make real-life investment decisions, it is beneficial to have a corporate perspective present in the analysis of cost-effective emission control. In conclusion, the main implication of our results is that sensitivity over interest rates should be included in future analysis of cost-effective air pollution control.

Our analysis is made in an air pollution policy context, but the patterns we identify should be applicable to other environmental as well as climate policies. Cases when investment perspectives can be important for environmental policy instrument design are for example: when designing policy instruments to achieve cost-effective pollution control; when calculating and communicating marginal abatement cost (MAC) curves for pollution control; and when analysing desirable pollution tax levels.

Our results also complement ongoing research on policy instruments for control of multiple pollutants. Earlier studies—although focusing mainly on the interplay between greenhouse gases and air pollutants—have, for example, identified that strategic corporate behaviour in emission permit markets might lead to cost inefficiencies (Dickson and MacKenzie 2018). It is also identified that the choice between an emission tax and permit instruments on different pollutants in a multi-pollutant system might have welfare impacts, where the key determinant is whether the pollutants are complements or substitutes (Ambec and Coria 2013; Fullerton and Karney 2018). Furthermore, also related to our results, Ambec and Coria (2018) and Antoniou and Kyriakopoulou (2015) show how the best choice of instruments is affected by the geographical dispersion of emissions and the national/international structure of governance. Our results add yet another dimension to this ongoing research on cost-effective multi-pollutant environmental policy by showing how also investment perspectives can affect cost-effectiveness of a policy. The next step for research should be to identify which policy instruments that have the potential to alleviate the effect of investment perspectives on emission control.

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